**ADVISER: A SOFTWARE TOOL FOR EVALUATION AND RATING OF NUMERICAL MODELS IN CRASH SAFETY ANALYSES**

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**ABSTRACT**

Increasingly stringent international passenger safety norms and the need to reduce vehicle body weight for environmental and protection requirements demand efficient and innovative design methods. Computer simulation, or virtual testing, allows an integrated evaluation of these aspects in the early design stages and thereby reduces costs for prototyping and time-to-market.

This paper deals with the application of virtual testing in vehicle passive safety design to:
(1) reduce injury numbers by enhancing passive safety for a wide range of conditions, and
(2) reduce the duration and costs of the vehicle design by improving the efficiency of the design process.

A software tool, called ADVISER, was developed to facilitate the use of virtual testing in automotive safety design and regulations. ADVISER contains the following modules: 1) procedures and guidelines to standardise and rate numerical models and simulations; 2) stochastic modelling to accounting for the experimentally observed scatter in simulations; and 3) a validated virtual test procedure to extend the range of protection beyond current regulations to real life crash conditions. All steps needed for acceptance of this virtual test procedure in regulations or in a consumer test method will be taken into account.

**INTRODUCTION**

Increasingly stringent international passenger safety norms and the need to reduce vehicle body weight for environmental and protection norms require efficient and innovative design methods. Computer simulation, or virtual testing, has grown to be an efficient tool in vehicle design for aspects such as passive safety, vehicle dynamics, durability, ergonomics, and styling. Virtual testing allows integrated evaluation of such aspects in the early design stages and thereby reduces costs for prototyping and reduces time-to-market.

The European project VITES focuses on the application of virtual testing in vehicle passive safety design. In this project, a validated virtual testing procedure will be developed with the following prime objectives:
*1. To reduce injury numbers by enhancing passive safety for a wide range of conditions*
*2. To reduce the duration and costs of the vehicle design by improving the efficiency of the design process.*

The project aims to increase the status of virtual testing to a comparable level as attained in current regulated crash-test procedures. This will enhance the application of virtual testing in support of current regulated test procedures and will contribute to the development of new standards in the automotive industry. The ultimate goal is to have virtual testing accepted as part of regulated or normative procedures for passive safety evaluation.

A strategy was adopted to achieve the above-mentioned objectives by 1) developing procedures and guidelines to standardise numerical models and simulations; 2) accounting for the experimentally observed scatter in simulations by stochastic modelling; and 3) use virtual testing to extend the range of protection beyond current regulations. A software tool, called ADVISER, was developed to facilitate the implementation of this strategy in passive safety design and regulations. ADVISER was developed together with another European project, called ADVANCE. The remainder of this paper will provide a detailed description of the current capabilities of ADVISER and ongoing developments.

## STANDARDISATION OF NUMERICAL MODELS

Virtual testing is already widely applied in vehicle passive safety design. A number of numerical methods are commonly used to model the physical events in a car crash at various levels of detail (e.g., finite element and multibody) [1]. However, these numerical methods do not produce similar results in all cases. In addition, a range of models with varying quality exists for all components involved in a car crash, including models of the occupant, restraint system, vehicle, and impactor.

Of these components, the models of the regulated crash dummies are the most extensively validated. However, a user might not always be aware of the level of validation of these dummy models and can, therefore, inadvertently use the model beyond its validated range. Since vehicles and restraint systems are generally developed under high time pressure (within months), their numerical counterparts are mostly validated against a very limited number of impact conditions. Due to the complex deformation response of barriers in crashes, the predictive capabilities of barrier models are still limited.

In addition, in many cases the same experimental data or data collected under comparable conditions have been used to validate different models. Thus what is shown as “validation” is actually more a “fit of experimental data” or “tuning”. Consequently, when these models are applied beyond their validated range, simulation and testing sometimes shows different trends.

To make matters even more complicated, objective criteria to rate the correlation between numerical and experimental data are lacking, resulting in highly subjective ‘validation’ of models. Consequently, models that describe the same physical situation, but which have been developed and validated at different sites and/or with different tools cannot be compared directly.

This situation greatly hinders the acceptance of virtual testing as part of occupant safety regulations and calls for the definition of general procedures to create validated models and objective criteria to rate the numerical results. The availability of such procedures and guidelines is an essential step towards the application of virtual testing in regulated crash safety assessments.

The VITES project covers the various aspects related to the definition and application of procedures and criteria allowing an objective assessment of the quality of models and of the accuracy of the virtual test results obtained. An extensive literature search into existing correlation methods and corresponding criteria was performed. The most suitable correlation criteria were evaluated in detail for their applicability in passive safety design and regulations. Those criteria that were found suitable were implemented in the software tool ADVISER, which stands for ADvance and VItes Simulation, Evaluation, and Rating. ADVISER is developed together with the ADVANCE project.

ADVISER automatically correlates experimental and numerical data and based on this provides a quality rating for the numerical model. ADVISER contains pre-defined correlation and rating procedures for the various numerical models typically used in car crash simulations, such as occupants (dummy and human), restraint systems, vehicles, and barriers. In addition, the evaluation tool provides the user with the ability to follow their own validation procedure by using existing or user-defined correlation criteria. The model quality rating is expressed in terms of ‘virtual stars’, similar to the NCAP rating for vehicles. Figure 1 presents a general overview of the ADVISER approach. ADVISER currently interfaces with all codes commonly used in crash safety simulations, such as MADYMO, RADIOSS, LS-DYNA, and PAM-CRASH.

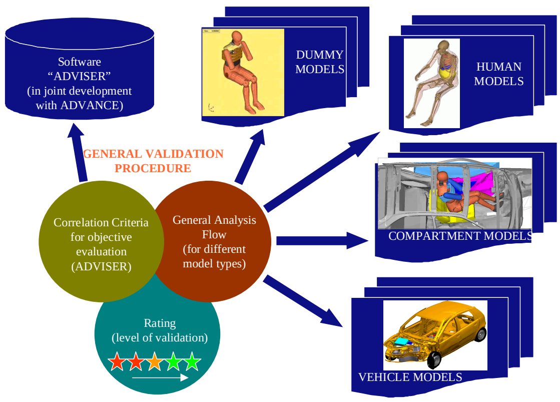


**Figure 1. Overview of ADVISER methodology**

Figure 2 and Figure 3 provide examples of how ADVISER can be used to evaluate the predictive quality of a Hybrid-III dummy model. In Figure 4 an overview is given of the ADVISER approach to simulations of normative crash tests, such as EURO-NCAP.

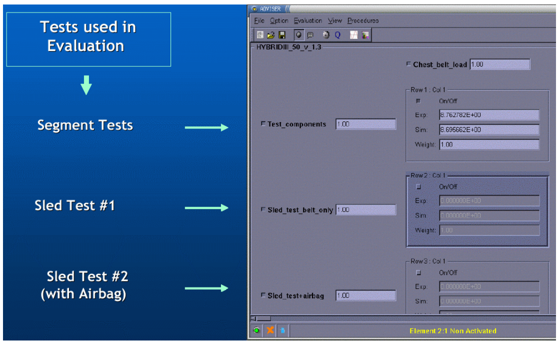


**Figure 2. Example of ADVISER evaluation procedure  for Hybrid-III dummy model**

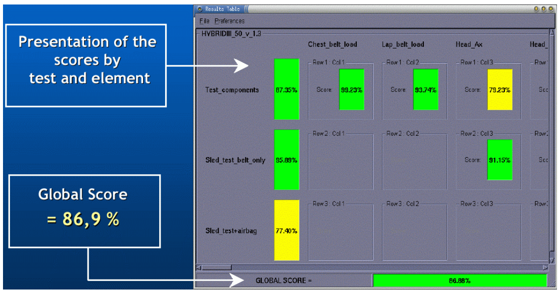


**Figure 3. Example of ADVISER correlation results for Hybrid-III dummy model**

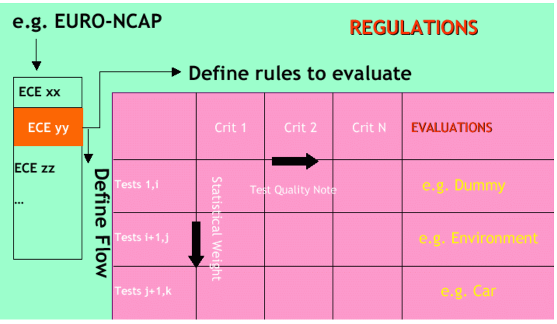


**Figure 4. Overview of ADVISER procedure for EURO-NCAP simulations**

One of the ongoing activities is the application of ADVISER to computer models currently used in automotive passive safety design to demonstrate the state of the art in virtual testing. Results will indicate the accuracy that can be obtained with virtual testing, but will also show where numerical simulations are not yet sufficiently predictive and further research is needed to better capture the physical system.

Existing models of crash dummies, humans, vehicles, restraint systems and barriers will be evaluated according to these general validation procedures. These models will be validated for applications under a range of impact directions (frontal, side, oblique) and velocities. In the case of a model that does not pass the validation criteria, it will be enhanced. A database of existing experimental data is currently being created to serve as a common basis for model validation. Additional experiments will be performed in case there is not sufficient existing data for a particular model and/or loading direction.

ADVISER will also include an objective method to analyse and rate overall injury risks for a specific vehicle design for a range of conditions and for injury criteria representing different body parts. Such a method is needed to systematically evaluate safety for real-life crash conditions.

Even though the focus of the VITES and ADVANCE projects will be on passenger car occupant protection, the methods developed will be sufficiently general to be applicable to other accident scenarios. This will enable the virtual assessment of safety in rollover and rearward loading, and the protection of vulnerable road users such as pedestrians [2], [3].

## STOCHASTIC SIMULATIONS

The inherent variability of the mechanical systems comprising a crash test leads to a substantial scatter of results. This means that when a vehicle meets requirements in one or more tests performed by the manufacturer, a repeated test by, for example, a consumer organisation may lead to substantially different results (Figure 5). The high costs involved in full car crash tests inhibit a comprehensive experimental characterisation of the range in safety ratings and injury predictions induced by scatter. Virtual testing can provide an efficient solution to this problem.

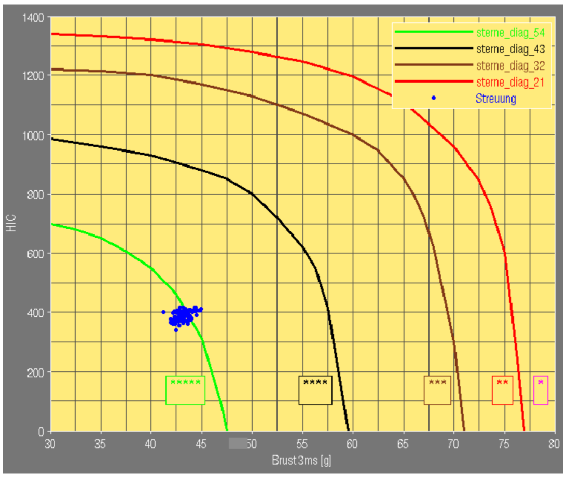


**Figure 5. Effects of scatter on HIC rating in US NCAP test, courtesy of BMW.**

However, the numerical tools generally used in crash safety design are purely deterministic and aim at predicting the average response of the physical system. These deterministic models cannot reproduce the scatter in the components and will provide identical results for repeated simulations. Therefore, in order to account for scatter in the vehicle design, stochastic modelling techniques need be incorporated [4].

Within the VITES project, a method has been developed to predict the stochastic response of crash tests in relation to the scatter of the component responses in the system. This stochastic method has been implemented in ADVISER and a stochastic Hybrid-III dummy model has been developed. The approach taken in the stochastic analyses is presented in Figure 6.

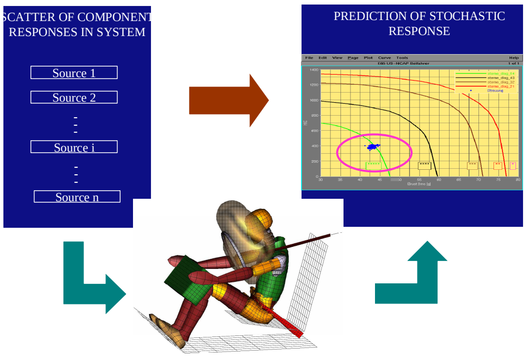


**Figure 6. Overview of stochastic approach in VITES project**

With this stochastic approach, the variability of regulated crash dummies will be evaluated and this research will also indicate areas where the current regulated dummy responses are insufficiently reproducible. The EC-funded project SIDECAR has already demonstrated that the variability of crash dummies is a major source of scatter. More recent studies have also indicated a large effect of the scatter in the Hybrid-III thorax on the NCAP-rating. A next step will be to systematically quantify this scatter for a sufficient number of dummies with different histories of usage and maintenance but falling within the calibration requirements.

The VITES project focuses on the stochastic response of the Hybrid-III dummy in regulated crash scenarios caused by the scatter in the dummy and its immediate environment (restraint systems and vehicle interior). An inventory has been made of the main parameters causing scatter in the injury ratings obtained from the Hybrid-III. A numerical sensitivity study was performed to rank these scatter parameters. A database of the experimentally observed scatter of the main parameters will be built. This data was mainly obtained from standardised certification tests and, additional tests that will be performed as part of this project.

Existing stochastic techniques were evaluated and the Monte-Carlo technique was found to be the most suitable starting point. A Monte-Carlo routine was implemented in ADVISER, together with advanced pre- and post-processing modules. ADVISER automatically generates the large numbers of data sets required for the stochastic analyses and starts the simulations (see Figure 7).

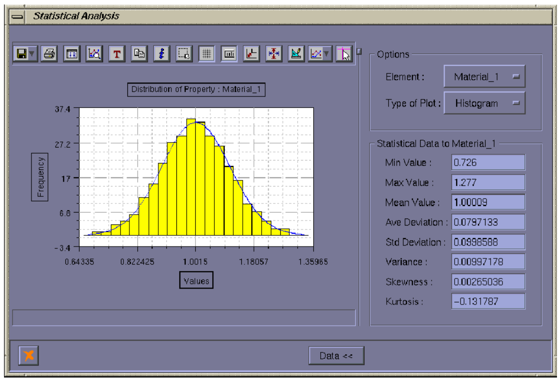


**Figure 7. Input of scatter data in ADVISER**

The vast amount of data resulting from the stochastical simulations can be automatically analysed, evaluated, rated, and presented in a number of comprehensible ways by ADVISER. Figure 8 and Figure 9 presented two possible ways to present the stochastic data in ADVISER by scatter plots and Principal Component Analysis. The automated data evaluation provides a convenient and comprehensive overview of the effects of scatter on the simulated response. General guidelines for stochastic virtual testing will be derived from the comparison between predicted and measured effects of scatter.

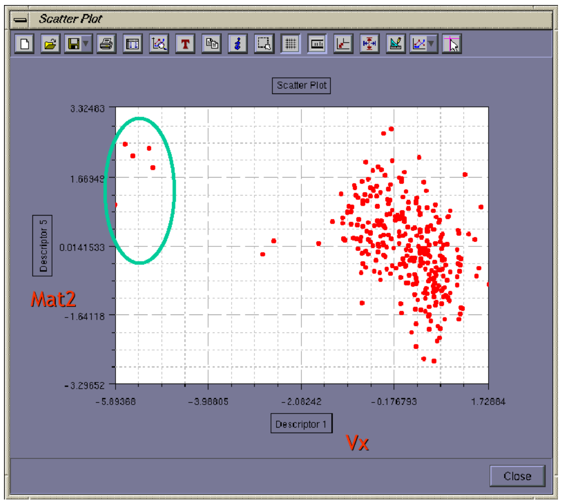


**Figure 8. Scatter plot of stochastical data**

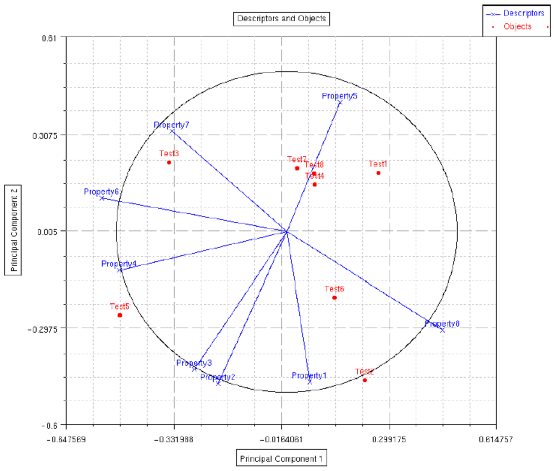


**Figure 9. Principal Component Analysis of stochastical data**

The existing MADYMO model of the Hybrid-III was adapted to incorporate the stochastic modelling techniques required for the scatter analyses. The scatter found experimentally was related to scatter of physical model parameters and the requirements for stochastic models to predict scatter in crash simulations were defined. The stochastic model is currently evaluated using scatter data obtained from a large number of Hybrid-III certification tests.

## EXTENDING THE RANGE OF PROTECTION

Current regulatory and consumer tests for cars are based on a small number of precisely defined test conditions using a $50^{th}$ percentile dummy seated in an average driving position. As a result, there is a concern that car designs may have become optimised to protect their occupants under this small range of crash conditions, with the result that occupants may now be at greater risk in other, non-tested conditions including lower severity crashes.

Previous research has resulted in data on the occurrence of impact conditions other than those used in regulated crash tests. Figure 10 shows the frequency distribution of the impact direction, obtained from the CCIS database (UK). The figure shows that frontal head-on impacts are most common, but that oblique impacts occur frequently as well. These oblique impact directions are currently not accounted for in regulated tests.

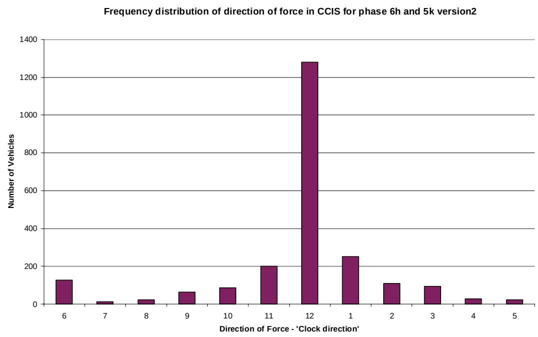


**Figure 10. Frequency distribution of impact direction, obtained from CCIS database, courtesy of TRL. The notation uses clock directions, where 12 is head-on, 9 and 3 are side-on, and 6 is rear.**

In the same way, impact speeds for frontal and side impacts have a wide distribution. Figure 11 and Figure 12 present the frequency distribution of side impact closing speeds with near-sided belted occupants with MAIS 3+ or fatal outcome, respectively. The data was obtained from the CCIS database (UK) and the arrow represents the regulatory test speed. These figures clearly indicate that the regulated test speeds account for only 50% of the occupants sustaining serious or fatal injuries. However, the figures also show that a considerable number of occupants get seriously injured or even killed at much lower impact speeds than those prescribed in the regulated tests.

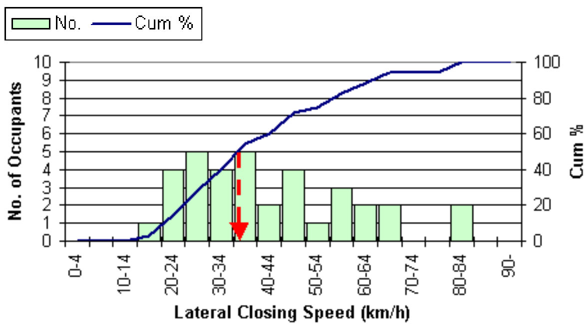


**Figure 11. Frequency distribution of impact closing speed in side impacts with near-sided belted occupants with MAIS 3+, courtesy of TRL. The arrow represents the regulatory test speed.**

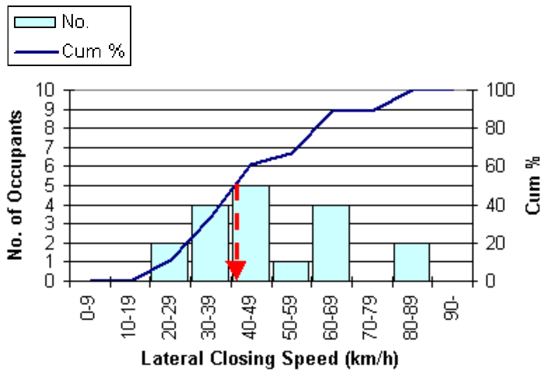


**Figure 12. Frequency distribution of impact closing speed in side impacts with near-sided belted occupants with fatal outcome, courtesy of TRL. The arrow represents the regulatory test speed.**

Occupant size and proportion also vary widely in real world accidents and hence the regulatory tests with only 50th percentile dummies may be inadequately protecting other sizes of occupants. Figure 13 demonstrates the wide distribution of occupant heights in real-world crashes. Mathematical occupant models in different body sizes have been developed by scaling dummy models towards human anthropometric data [5], but a systematic method to cover a range of scenarios by virtual testing is still lacking.

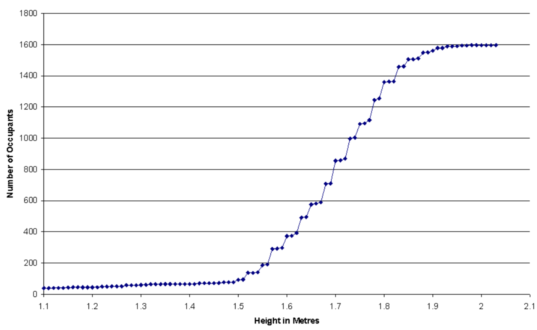


**Figure 13. Frequency distribution of occupant heights, obtained from CCIS database (UK), courtesy of TRL.**

Theoretically, a wide range of scenarios could be considered by crash tests with a variety of dummy sizes. However, costs for testing would rise proportionally to the number of conditions tested, whereas virtual testing would cost very little once validated models are available. Thus virtual testing has great potential to extend the range of protection to real life crash conditions, but this potential has not yet been explored.

Within the VITES project, a validated virtual test procedure will be developed to extend the range of protection beyond current regulations to real life crash conditions. Accident databases have been analysed to identify possible gaps in current regulations where occupants are not optimally protected. These gaps will be evaluated in extensive simulations for a range of impact directions (frontal, lateral, intermediate), impact velocities, occupant body sizes and postures. A validated virtual test procedure will be proposed to fill these gaps. All steps needed for acceptance of this virtual test procedure in regulations or in a consumer test method will be taken into account. The virtual test procedure will be implemented in ADVISER to facilitate its application in vehicle safety design and regulations.

## DISCUSSION

The VITES project deals with virtual testing in vehicle passive safety design. A validated virtual testing procedure will be developed with the general objectives *to enhance passive safety and to gain efficiency in vehicle design.* The development and acceptance of such a virtual testing procedure will lead to more accurate and reliable virtual test results, while reducing the need for hardware testing. This will enhance the confidence in and the acceptance of virtual testing and will thereby allow major reductions in the duration and costs of the vehicle design process. Such a procedure will also be an essential step towards the application of virtual testing in regulated crash safety assessments.

The only European regulation for vehicle type approval by virtual testing so far is ECE Regulation 66, which relates to bus and coach safety for rollover. This regulation permits the use of computer simulation for the final prediction of structural strength and energy absorbing capability, on the condition that practical tests on vehicle components have been conducted to provide a sound basis for the characteristics and capabilities of the components that govern the performance of the whole structure [6].

The virtual testing procedure will also enable the assessment of the accuracy and reliability that can be obtained by virtual testing. This will lead to the identification of areas where current modelling techniques do not capture the physical events sufficiently accurately. This project will not deal with improving existing or developing new modelling techniques, but these items will be addressed within the ADVANCE project. Both projects will closely co-operate and exchange findings.

The virtual testing procedures developed in this project mainly focuses on currently applied regulated testing techniques using dummies. Meanwhile, validated models of the real human body have been developed in the EC-funded project HUMOS [7] (Figure 14). Human models offer improved biofidelity compared to crash dummies and potentially allow simulation of injury mechanisms at tissue level [8]. In the future, virtual testing could be largely based on human models . In addition to dummy based simulations the potential of real human models will be demonstrated in the VITES project.

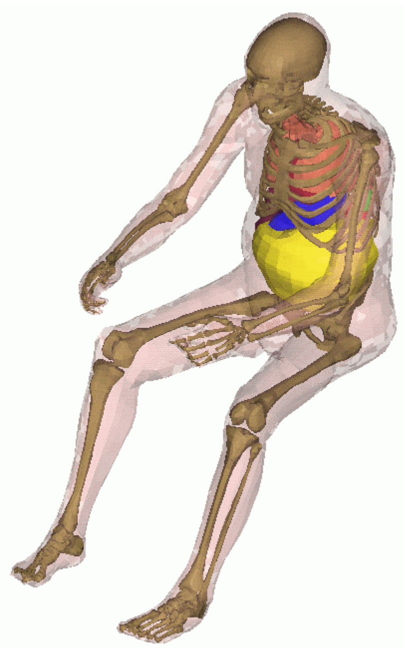

**Figure 14. Finite element model of the human body developed as part of the EC-funded project HUMOS.**

## VITES PROJECT

The VITES project is being undertaken by a consortium of partners comprising TNO, CRF, BMW, TRL, TRW, MECALOG, AUTOLIV, BASt, CIC, CIDAUT, Graz University of Technology, BASC, and Warsaw University of Technology. The project started on February 1, 2001 and has a duration of 36 months. For more information, see http://www.passivesafety.com/vites/.

## ADVANCE PROJECT

The ADVANCE project is being undertaken by a consortium of partners comprising MECALOG, DaimlerChrysler, Renault, TNO, CIDAUT, CADFEM, Politecnico Torino, Warsaw University of Technology, National Technical University of Athens.. The project started on February 1, 2001 and has a duration of 36 months.


## ACKNOWLEDGMENTS

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